

Flow-Structure Interactions in Presence of a Free-Surface

Donald Rockwell

Department of Mechanical Engineering and Mechanics

354 Packard Laboratory

19 Memorial Drive West

Lehigh University

Bethlehem, PA 18015

Phone: (610) 758-4107

Fax: (610) 758-4041

E-mail: dor0@lehigh.edu

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LONG-TERM GOALS

1. Establish the interrelationship between: (i) mechanisms of vortex formation from a cylinder in presence of a free-surface; (ii) unsteady loading on the cylinder; and (iii) onset and trajectories of the cylinder motion.
2. Develop and implement new techniques for acquisition of instantaneous, quantitative images of vortex patterns that are associated with the unsteady loading.

OBJECTIVES

1. Determine the structure of vortex formation from cylinders adjacent to a free-surface using quantitative imaging. Employ imaging techniques that yield a sequence of instantaneous spatial variations (space-time representations) of vortex development, in relation to the instantaneous loading on the cylinder, with the eventual aim of control of cylinder oscillation.
2. Develop and implement both externally-controlled and elastically-mounted cylinder systems, which allow assessment of the mechanisms of energy transfer between the fluid and the cylinder, and establish criteria for the onset of admissible trajectories of the cylinder oscillation in relation to the spectral content of the cylinder loading.

APPROACH

Experimental approaches are based on integrated experimental systems that allow either computer-controlled or elastic motion of the cylinder, high sensitivity force measurements, laser illumination, and dual-camera cinema techniques for acquisition of quantitative images. Post-processing of images involves a variety of approaches that take advantage of space-time representations of the vortex patterns, and their relation to the unsteady loading.

WORK COMPLETED

Experiments have been initiated, and in some cases completed, for generic configurations of horizontal and vertical cylinders in steady current, as well as in actual and simulated waves. The basic modes of

vortex formation have been related to the cylinder trajectory and the unsteady forces on the cylinder. These accomplishments are described below.

RESULTS

Wake from a Cylinder Undergoing Cross-Stream Oscillations

Critical features of oscillations of an elastically-mounted cylinder are simulated by controlled oscillations of a cylinder in presence of steady inflow (current). Previous experimental investigations have focused either on characterization of the unsteady forces or visualization of the wake. The present emphasis is on establishing the relationship between them, with emphasis on quantitative patterns of vortex formation in the near-wake. A universal form of the phase shift of the lift force, which occurs for frequencies at or near synchronization, has been deduced by representation of data from previous investigations and the present study on a suitably normalized plot. Quantitative images show that this phase shift is determined by a change in timing of the initially-formed vortex on either side of the phase jump. Further findings include a self-excited transition between wake modes at a fixed excitation condition.

Wake from an Elastically-Mounted Cylinder Undergoing Bimodal Oscillations

A cylinder is elastically-mounted such that it has a low mass-damping ratio, and a value of stiffness that is equal in all directions. Two high-sensitivity laser sensing systems allow acquisition of simultaneous records of the $x(t)$ and $y(t)$ displacements of the cylinder. The amplitudes of the $x(t)$ and $y(t)$ motions can exhibit severe modulations; moreover, the corresponding spectra may exhibit multiple peaks. These features have been critically assessed using various types of signal processing. The immediate goal is to characterize the nature of the bimodal oscillation as a function of reduced velocity.

Wake from an Elastically-Mounted Cylinder Undergoing Cross-Stream Oscillations Near and Piercing a Free-Surface

A cantilevered cylinder is oriented horizontally at a given elevation relative to a free-surface. The response of the cylinder system is characterized as a function of reduced velocity. Depending upon the degree of proximity of the cylinder to the free-surface, its response can exhibit severe hysteresis for decreasing, relative to increasing, values of reduced velocity. Moreover, it appears that a static stiffness criterion must be exceeded prior to the onset of oscillations close to the free-surface. These features do not exist for the classical case of the fully-submerged cylinder and will be interpreted in conjunction with quantitative visualization of the near-wake.

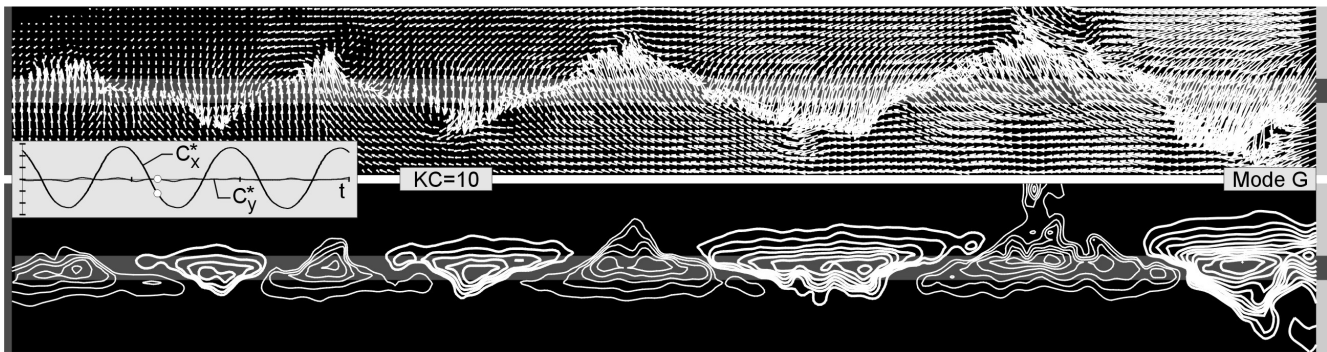
Wake-Cylinder Interactions Due to In-Line Oscillations in Presence of a Steady Current and a Free-Surface

Streamwise oscillation of a cylinder in a steady current simulates the case of a combined long wave and a steady current past a stationary cylinder. Phase-locking occurs between: patterns of vortex formation in the near-wake; the transverse force; and the motion of the cylinder. It is fundamentally different from the classical case of a cylinder undergoing transverse oscillations. For streamwise oscillation of the cylinder, the vortex formation and loading can have a period substantially longer than

the period of the cylinder motion. In presence of a free-surface, this type of phase-locked behavior can either be stabilized or destabilized, depending upon the gap between the free-surface and the cylinder.

Wake of a Stationary Vertical Cylinder in a Free-Surface Wave

A free-surface wave interacts with a stationary vertical cylinder. Simultaneous particle image velocimetry and shadowgraph techniques are employed in conjunction with instantaneous force measurements. Quantitative imaging of the instantaneous flow structure along the span of the cylinder and measurement of the instantaneous transverse force show that the well known, severe modulations of the force traces are actually associated with spontaneous transformations between generic types of three-dimensional modes of transverse vortex shedding. These observations have led to formulation of a probability density function for specification of the transverse force as a function of Keulegan-Carpenter number. This approach is of direct use to the designer and is a more representative indicator than time-averaged amplitude or spectrum.



Wave interaction with a stationary, vertical cylinder gives rise to organized, three-dimensional patterns in the wake of a cylinder. In the above images, the free-surface of the wave is at the right, and the bottom of the wave tank is at the left. Patterns of instantaneous velocity vectors (top image) and contours of constant horizontal velocity (bottom image) were acquired over a plane (laser sheet) located close to the base of the cylinder. These patterns correspond to a value of the transverse force coefficient $C_y \approx 0$; the in-line force coefficient C_x is relatively unaffected by the three-D mode.

Wake of Vertical, Elastically-Mounted Cylinder in a Free-Surface Wave

A vertical cylinder is suspended in a wave from the same elastic-support system as described in the foregoing case of bimodal oscillations of the cylinder in a steady current. The ratio of the wave frequency to the natural frequency of the cylinder system is crucial in determining the form of the cylinder trajectory, which can range from a simple unidirectional oscillation to a figure-eight or butterfly pattern. The patterns of shed vorticity are interpreted with respect to the instantaneous velocities of: the wave; the cylinder; and the wave with respect to the cylinder. Future efforts will employ high sensitivity position and force measurement techniques to characterize completely the elastic response in relation to quantitative imaging of the patterns of shed vortices.

Wake Structure and Loading from Oscillating Cylinders: Effect of Three-Dimensionality of the Near-Wake

Controlled orbital oscillation of a cylinder in steady current simulates the orbital wave motion past a stationary cylinder in presence of a steady current. The in-line force is relatively insensitive to the ratio of the horizontal to vertical axis of the elliptical trajectory of the cylinder. On the other hand, the transverse force coefficient varies remarkably with this ratio. Quantitative imaging of the near-wake shows the relationship between the quasi-two-dimensional vortex formation and the elliptical motion of the cylinder. Moreover, the three-dimensional patterns along the span of the cylinder are correlated with the type of orbital motion of the cylinder.

Wakes from Cylinders in a Tandem Arrangement

Stationary cylinders in a tandem arrangement generate patterns of vortices that are strongly dependent upon the gap between the cylinders. Quantitative images show, for small and large gaps respectively, that small- and large-patterns of vorticity generated in the shear layer buffet the downstream cylinder, retard the onset of flow separation from its surface, and substantially alter the form and timing of vortex shedding in its near-wake. These features are closely linked to the loading of the downstream cylinder.

Wake Structure from a Cylinder with Three-Dimensional Surface Treatment

A helical winding about a stationary cylinder in the form of a three-start helix can effectively retard the onset of large-scale Kármán vortex formation. This attenuation involves generation of three-dimensional patterns along the span of the cylinder, as characterized by quantitative imaging. Further investigations will address the consequence of this and other forms of surface treatment on the onset of self-excited oscillations of the cylinder.

Development of New Experimental Techniques

Use of continuous wave Argon-ion lasers, in conjunction with film-based, motor-driven camera systems has allowed development of dual camera arrangements, including a configuration that simultaneously acquires images from orthogonal, scanning laser beams. Transformation of these concepts to digital systems has continued during the past year, with the support of DURIP Grant N00014-99-1-0581 *A High Repetition Rate Laser for a Dual Space-Time Imaging System*.

IMPACT/APPLICATIONS

All of the foregoing projects involve acquisition of quantitative images of patterns of vortex formation in the near-wake of the cylinder. This type of fundamental understanding provides unambiguous interpretation of the underlying physics, as well as important cues for passive and active control of the vortex formation from both stationary and oscillating cylinders, in steady current as well as in wave systems. Moreover, such quantitative patterns can provide guidance for development of DNS and LES simulations. Furthermore, the corresponding dimensionless force coefficients and force spectra can be used immediately by the designer. Continued development of experimental techniques shows potential for application in a variety of experimental systems.

TRANSITIONS

During the past year, interactions have resulted in one or more of the following paths for transition: techniques for acquisition, processing and interpretation of quantitative flow and surface images; transfer of images for guidance of numerical simulations; and design of experimental systems and instrumentation. In many cases, the transfer of complementary information from these organizations to Lehigh was also accomplished. These organizations include: Electric Boat Corporation (Groton, Connecticut); Lockheed-Martin Corporation (Schenectady, New York); Thermosystems (TSI), Inc. (St. Paul, Minnesota); NASA Langley Research Center (Hampton, Virginia); Technical University of Denmark; Cornell University; Technical University of Istanbul (Turkey); Cukurova University (Turkey); and Monash University (Australia). Initial contacts have been made with Bristol University (England) and Genoa University (Italy).

RELATED PROJECTS

The present program serves as the parent grant for DURIP Grant No. N00014-99-1-0581, which allows development of digital image acquisition systems. Related instrumentation obtained from the National Science Foundation (NSF) and the Air Force Office of Scientific Research (AFOSR) has further aided development of imaging systems. Complementary research programs in the area of unsteady separated flows and flow-structure interaction include the topics of shallow water vortex systems (NSF), buffeting of aerodynamic surfaces (AFOSR) and flow tone generation past shallow cavities (ONR).